Thin, lightweight, low frequency acoustic projectors for shallow water environments

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ABSTRACT

Abstract – Miniature flextensional transducers, called cymbals, have been incorporated into thin, lightweight, large area panels for use as low frequency acoustic projectors in shallow water. The prototype panels, measuring 100-mm by 100-mm by 6.35-mm thick exhibit a high acoustic output at a relatively low in-water resonance frequency. Furthermore a second resonance frequency that is over an order of magnitude higher suggests that the panel may be used to provide sound output over almost a two decade frequency band. The mass of the unpotted panel is less than 150 grams and the total thickness is 6.35 mm. The cymbal panels are believed to be excellent candidates as acoustic projectors on autonomous and/or unmanned underwater vehicle platforms as well as other shallow water platforms where low frequency, light weight and high acoustic output are desired.

Keywords: cymbals, flextensional transducers, shallow water, projectors

INTRODUCTION

There is currently an interest in identifying objects underwater based upon their acoustic fingerprints[1, 2]. This structural acoustic approach is typically performed at frequencies between 1-kHz and 10-kHz with particular emphasis at 1 kHz. In addition to low acoustic attenuation, which permits long range detection, low frequency acoustic waves are also able penetrate into sediments which thus allows for the detection and identification of buried objects.

In order to implement this new detection and identification approach on autonomous underwater vehicle (AUV) and unmanned underwater vehicle (UUV) platforms, advanced acoustic transduction hardware is required[3]. Traditionally, free-flooded piezoelectric ceramic rings, electromagnetic drivers, or flextensional transducers have been used to generate high acoustic output at low frequencies. However, due to their large size and weight, these technologies are not easily adaptable or convienent for AUV and UUV platforms.

Cymbal actuator technology was developed at Penn State's Materials Research Laboratory in University Park, PA in the mid 1990's[4]. The cymbal is essentially a miniature class V flextensional transducer[5]. It consists of a piezoelectric or electrostrictive ceramic disk poled in its thickness direction which is sandwiched between and mechanically coupled to two thin metal caps, each of which contains a shallow air-filled cavity on its inner surface (Figure 1). The caps serve to convert and amplify the small radial displacement and vibration velocity of the ceramic disk into a much larger axial displacement and vibration velocity normal to the surface of the caps. The increase in velocity is at the cost of force, however piezoceramics are capable of higher force output then is often needed for many acoustic applications where higher acoustic output is desired.

Cymbals were initially investigated as a potential underwater sound projector in both single element and array form[6]. The individual cymbal elements were incorporated into a 3 by 3 nodally mounted array (with a radiating area of $\approx$ 11.4 cm^2). Both potted and unpotted (oil-filled) arrays were calibrated. The peak transmitting voltage response (TVR) of these arrays were nominally 134 dB//1μPa/V at their resonance frequency of 18-kHz. It was found that the polyurethane layer damped the response of the potted array by damping the flexural motion of the caps.

Studies have also shown the effects of hydrostatic pressure on the performance of the cymbal is dependent upon the stiffness of the cap material as well as the cap shape[6]. For the particular cymbal drivers used by NRL for panel Design 2, the

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measured response was essentially unchanged up to a hydrostatic pressure of 2.5 MPa (250 m water depth). These reported results indicate that cymbal technology is best suited for shallow water environments. As seen in individual cymbal element studies[6], the tradeoff in the cymbal panel performance can be compromised for higher hydrostatic pressure conditions at the cost of the peak acoustic output.

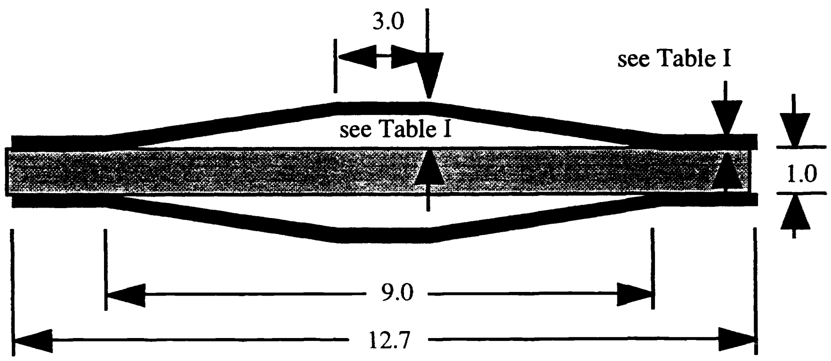


Figure 1: Single cymbal flextensional driver element (dimensions in mm).

Table I Cymbal Actuator Panel Design Types

	cymbal cap thickness	cap cavity depth	cap material	panel designation
Design 1	0.20-mm	0.16-mm	brass	G8x8-1
Design 2	0.25-mm	0.32-mm	brass	7x7TC-B1
			titanium	7x7TC-T1

In order to lower the resonance frequency of the cymbal drivers by an order of magnitude, they have been mass loaded by placing them between two stiff cover plates[3, 7]. Nevertheless, the panels still weigh less than 1.5 N. This panel configuration is akin to that of a 1-3 piezocomposite structure with coverplates, where the cymbal actuators replace the function of the ceramic rods. A schematic of the panel construction is shown in Figure 2. Such panels were evaluated in-air by laser Doppler vibrometry (LDV) to determine surface displacement and panel vibration modes. It was found that the coverplates move in a pure piston-like motion at frequencies below the panel resonance (< 2-kHz)[7]. Work is now underway at the Naval Research Laboratory to develop these thin, lightweight actuator panels as low frequency acoustic projectors for use in shallow water applications.

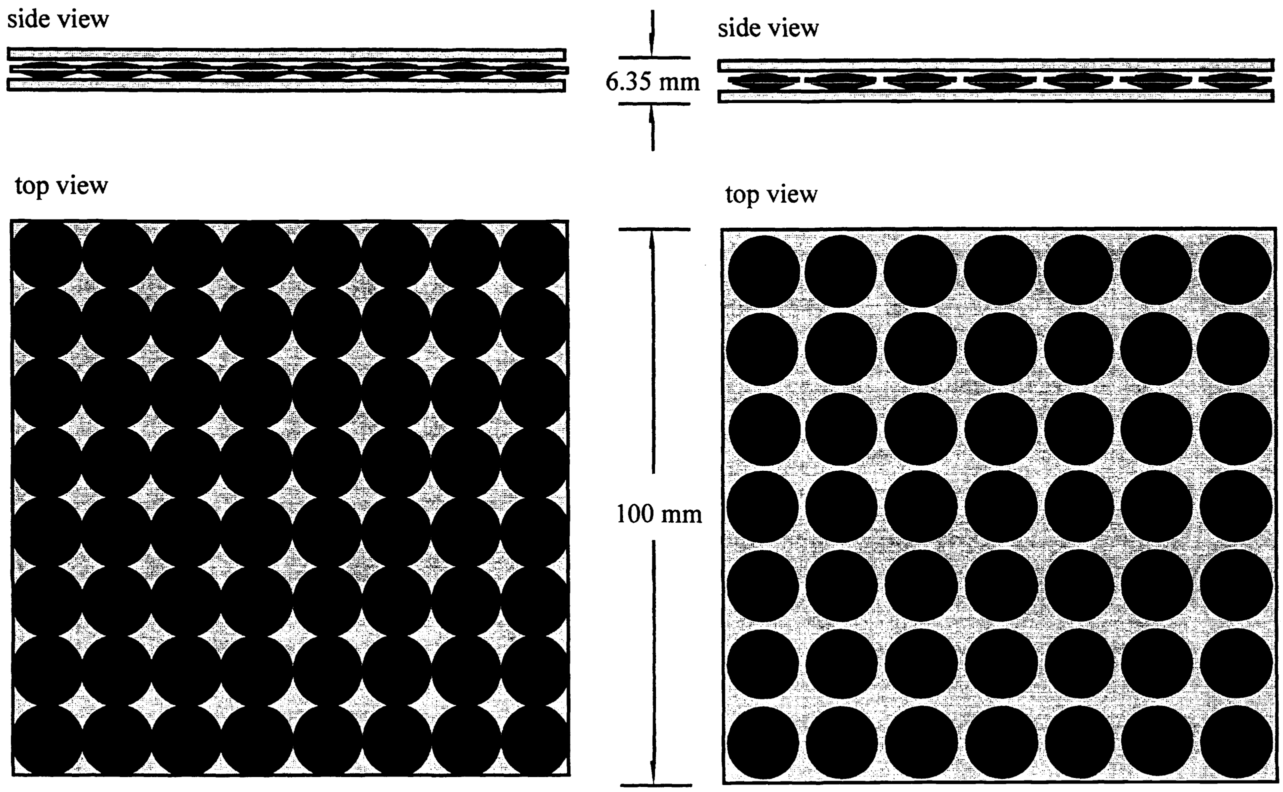


Figure 2: Top and side views of the two cymbal panel designs (8x8 is on the left and 7x7 is on the right).

1. PANEL CONSTRUCTION

The individual cymbal driver elements were fabricated at Penn State's Materials Research Laboratory in University Park, PA. The caps were prepared by cutting blank disks from a sheet of the desired metal and then shaping them using a die press to produce the desired dimensions. The caps were bonded to a poled PZT disk (Navy Type VI) using a screen printed layer of epoxy approximately 20 μm thick and 1.8 mm wide. Finally, the assembled cymbals were cured for 4 hours at 65° C while under moderate pressure. The cymbal elements were characterized in-air by measuring their electrical immittance (admittance/phase) spectra and effective piezoelectric d_{33} coefficient at the apex of the cap. These data are informative as to the quality and alignment between the caps and ceramic[8].

The cymbal elements were incorporated into panels at the Naval Research Laboratory in Washington, DC. A square array configuration of closely packed cymbals were sandwiched between two stiff 100-mm by 100-mm by 2.2-mm thick graphite cover plates from Aerospace Composite Products, San Leandro, CA. A silver conductive epoxy was used to attach the cymbals to the copper electroplated cover plates.

Two different actuator panel designs were investigated and compared. Design 1 consisted of sixty-four cymbals arranged in an 8x8 arrangement, whereas Design 2 consisted of forty-nine cymbals in a 7x7 arrangement. Figure 2 shows the front and side views of the two panel designs. The dimensions and cap materials used for the cymbal drivers in the two panel configurations are presented in Table I. When the cymbals are in an 8x8 arrangement, electrical shorting occurs due to the cymbals touching one another. This has been eliminated in the 7x7 designs, which contain a narrow gap between the driver elements.

2. IN-AIR IMMITANCE DATA

The in-air electrical immittance as a function of drive frequency for the actuator panels was measured using a HP 4192-A Impedance Analyzer. The measurements were conducted with the samples on soft surfaces, which essentially constitutes a free-free boundary condition. The fundamental resonance frequencies for the cymbals, both individually and when in a panel configuration, are given in Table II.

Table II Measured In-Air Resonance Frequencies of the Cymbal Panels

Panel	cymbal only	unpotted panel	potted panel
G8x8-1	17-kHz	4845 Hz	3385 Hz
7x7TC-B1	26-kHz	7405 Hz	4145 Hz
7x7TC-T1	36-kHz	8085 Hz	4345 Hz

The cymbal only data refers to the in-air flexural resonance frequency of a cymbal element by itself in a free-free testing condition. Note that once the cymbal elements are placed in the panel arrangements, the panel resonance frequency is only 25% that of the individual element. The addition of the potting also causes the panels to drop in resonance frequency. This drop is directly related to the addition of the mass load of the rho-c polyurethane encapsulant.

In addition to the in-air immitance data, a full study of the in-air displacement profile, as determined using laser Doppler vibrometry (LDV), has been conducted[7]. The results of that study suggest that the low frequency resonance is primarily due to the size of the individual cymbal elements and spacing between neighboring elements in addition to the mass of the cover plates.

3. UNDERWATER CALIBRATION

Prior to performing underwater calibration studies, the edges of the cymbal panels were wrapped with a butyl rubber tape, then potted in polyurethane. The purpose of the rubber tape was to prevent the polyurethane encapsulant from entering the air cavity between the cover plates and the cymbal elements. It was found that if polyurethane infiltrates this air space, the flexural motion of the cymbal caps becomes strongly damped. In panels where polyurethane has entered the cavities, the transmitting performance of the panel is comparable to that of a similar 1-3 piezocomposite at frequencies below 100-kHz[3]. By maintaining the air space between the cover plates and cymbal drivers, the flexural motion of the cymbal caps is not damped and consequently the high panel displacements noted during in-air LDV measurements[7] are realized underwater.

Standard underwater transducer calibration measurements were performed at the NSWC/Crane Glendora Lake Facility in Sullivan, IN. Table III compares the TVR and Qm for the panels at their respective in-water resonance frequencies. This resonance frequency is the mass loaded cymbal flexural resonance frequency where the mass loading is the water.

Table III Cymbal Panel Underwater Calibration Data

Panel	TVR (dB//µPa/V)	@ *fr*	Qm
G8x8-1	119	1900 Hz	2.1
7x7TC-B1	130	1750 Hz	4.4
7x7TC-T1	131	1850 Hz	3.7

The transmitting voltage response (TVR) vs. frequency curve for the 7x7TC-T1 panel is shown in Figure 3. This curve is representative of both 7x7 panel designs. This response demonstrates the high acoustic output at the flexural resonance frequency of 1.8 kHz. After a 12 dB drop at 7.4 kHz, the transmitting response output increases up to 50 kHz. This behavior suggests that this transducer may also be accommodating for wide band and higher frequency applications.

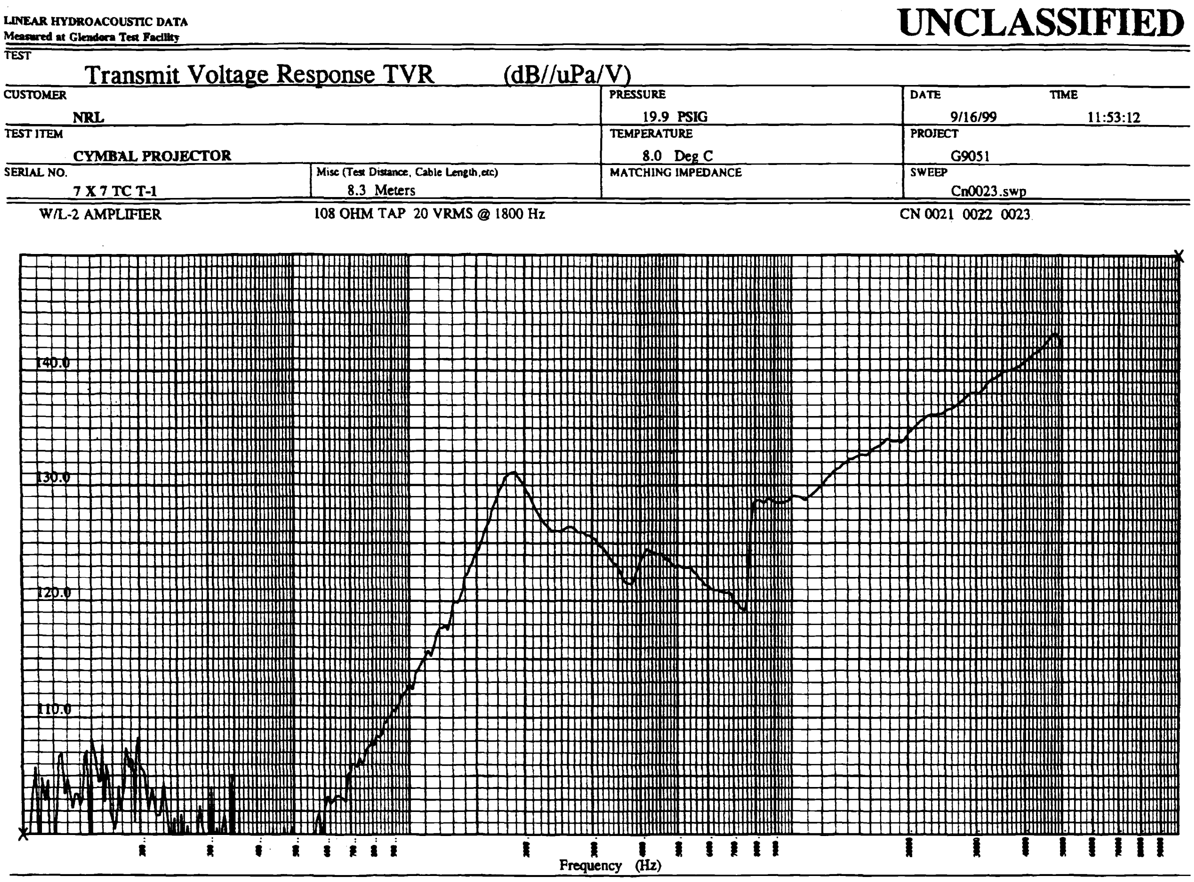
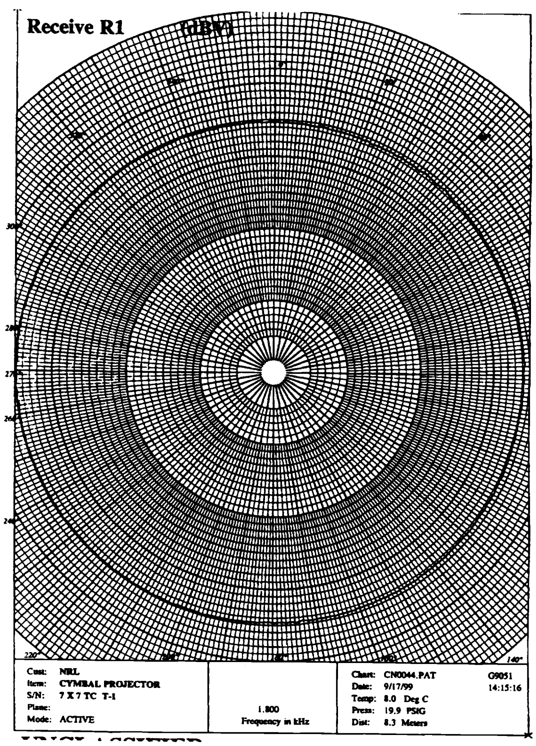


Figure 3: Transmitting voltage response vs. frequency for cymbal panel 7x7TC-T1.

Figure 4 shows the respective beam patterns for this same panel at 1.8-kHz (*fr*) and 10-kHz. For the 8x8 panel, some polyurethane did partially infiltrate the air cavity during processing, which resulted in a damped acoustic output. This permeation has resulted in the 12-dB reduction in response as compared to the 7x7 panel configurations. This lower output is also a function of the lower generative force from the cymbal elements due to their thinner caps and shallower cavities.



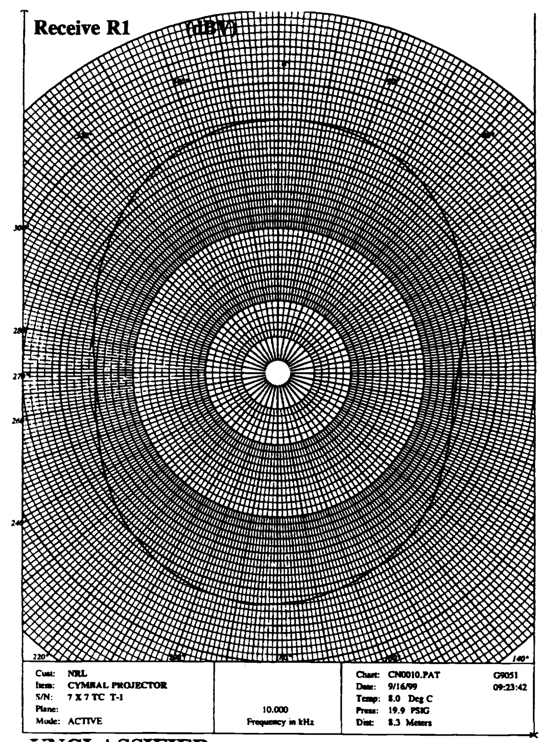


Figure 4: Acoustic directivity patterns of cymbal panel 7x7TC-T1 at 1.8 kHz (on left) and 10 kHz (on right).

The sound pressure level (SPL) vs. frequency for the 7x7TC-T1 panel is shown in Figure 5. The four response curves show the sound output of the panel for drive levels of 20, 100, 500 and 100 (after high drive exposure) Volts (rms), respectively. When driven at 500 Vrms, the panel resonance frequency decreases from 1850-Hz to 1750-Hz and begins to flatten out. The beam patterns also changed from symmetrical to unsymmetrical. The 100 Vrms after high drive response on Figure 5 is the SPL when the drive level was returned to 100 Vrms after being driven at 500 Vrms. The SPL dropped 4-dB from the initial 100 Vrms drive response after the 500 Vrms drive exposure. From the transmitting power response (TPR) and beam patterns, the transducer efficiency at 1.8-kHz was calculated to drop from 72% (at 20 Vrms) to 27% (at 500 Vrms) as the drive level increased. After the conclusion of the electroacoustic measurements, this particular panel was dissected to try to determine the cause of the performance degradation. It was found that several of the cymbal elements became detached from the cover plates due to failure of the conductive epoxy attachment. This failure resulted in several cymbal elements becoming detached from the radiating panel and thus the performance was similarly degraded because of the reduced number of drive elements. It was also found an area under the radiating plate which had been burned due to obvious arcing between the cymbal caps and the electroplated radiating top plate.

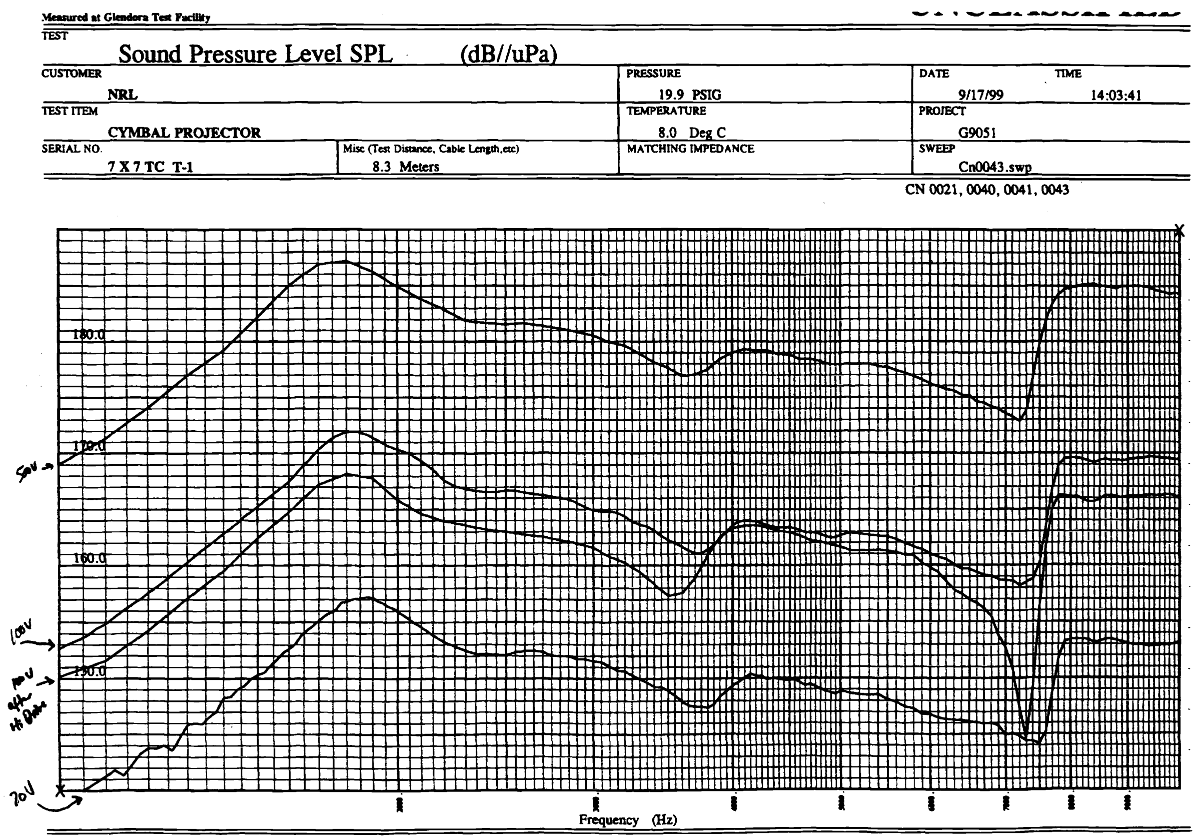


Figure 5: Source level vs. frequency for cymbal panel 7x7TC-T1.

4. FUTURE RESEARCH DIRECTIONS

Current 2000 research has concentrated on improving the mounting arrangements of the cymbals to the radiating plates. This research has resulted in an improved method for mechanically attaching the cymbal elements to the carbon epoxy plates. This mechanical attachment arrangement also eliminates the electrical conductive attachment plane from the underside of the radiating plate to the top of the plate while eliminating the electroplated inner surface. This improvement is expected to result in higher input voltage capabilities and thus, high acoustic output.

CONCLUSIONS

Cymbal-based projector panels exhibit relatively high acoustic output at low frequencies in shallow water. After the low frequency resonance frequency, the acoustic output has been shown to continue increasing over a multidecade frequency range. It has also been found that the maintenance of the air matrix cavity between the cover plates is essential in order to achieve high acoustic output and symmetrical beam patterns. The cymbals with the relatively thicker (and hence, stiffer) caps, in conjunction with the 7x7 element arrangement, show the most promising acoustic behavior as a proper mix of generative force and displacement characteristics for shallow water applications.

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